Beam Transport of 4 GeV Protons from AGS to the "Proton Interrogation Target" of the "Neutrino line" ("Z_line") and Effect of the Air on the Transported Beam.

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Abstract

As part of the preparation for the Proton Interrogation Experiment, we have calculated the beam optics for the transport of 4 GeV protons, from the AGS extraction point, to the "Cross-Section Target Wheel 1" and to the "Proton Interrogation Target". In this technical note we present three possible beam-transports each corresponding to a particular Fast Extracted Beam (FEB) setup of the AGS.

In addition we present results on the effect of the atmospheric air, (which fills the drift space of the last 100 [m] of the transport line), on the size of the beam, at two locations along the drift space, one location at the middle of the drift space and the other at the end where the "Proton Interrogation Target" is placed.

All the beam transports mentioned above require the removal of the WD1 dipole magnet, which is the first magnet of the W_line, because it acts as a limiting beam aperture, and the magnet is not used in the beam transport. An alternative solution of a beam transport, which does not require the removal of the WD1 magnet, is also presented. In this solution, which models the transport line using the TURTLE computer code[7], the vertical beam sizes at the location of the WD1 magnet is minimized to allow "lossless" beam transport at the location of the WD1 magnet. A similar solution, but using a MAD model of the line, is also presented.

Introduction

The "Proton Interrogation Experiment" requires a beam intensity of $\sim 10^{11}$ protons at 4 GeV, which can be contained in a "single beam bunch" or a "few bunches" (up to four) all delivered at the target within few μsec. The time interval between two consecutive deliveries of a "single beam bunch" or "few bunches" is ~ 5 min.

Beam bunches will be extracted from the AGS using the Fast Extracted Beam (FEB) system [1] and will be transported to the location of "Cross-Section Target Wheel 1" or to the location of the "Proton Interrogation Target", shown in Fig. 1 which is an aerial view of the Collider Accelerator Complex (CAD).
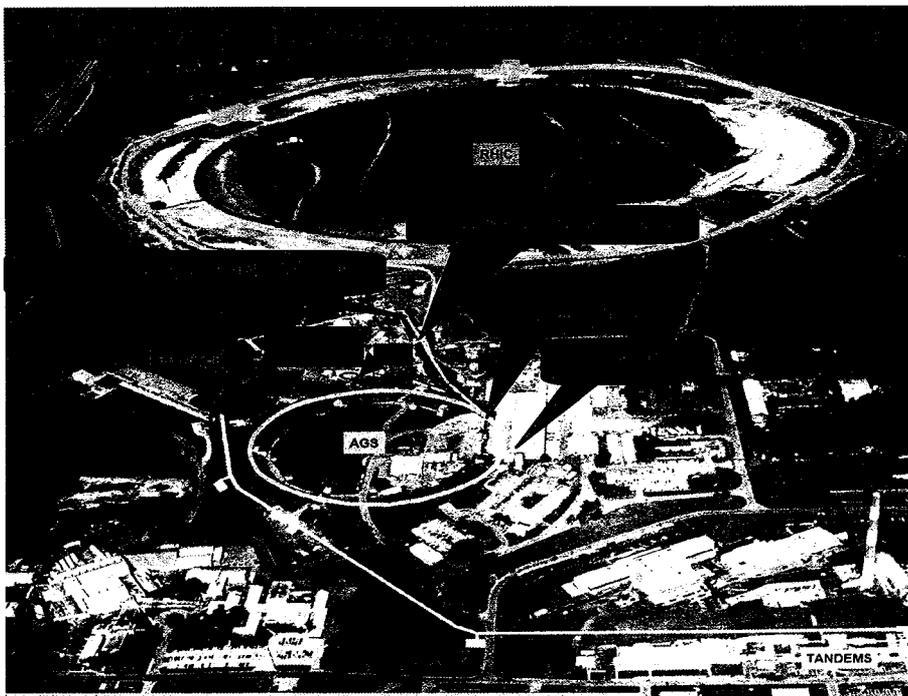
The proton beam will be pre accelerated by the TANDEM or LINAC, followed by additional beam acceleration in the Booster, which is shown in Fig. 1. In the same figure, also shown, is the AGS synchrotron (yellow circle) where the beam will be accelerated to 4 GeV and will be circulating, before it is extracted from the AGS, by the "G10_kicker" which is located at the AGS straight section G10, and is indicated in Fig. 1 by the Green box with the label "G10_kicker". The beam transport line which is shown by the yellow line, starts at the location of the G10_kicker and ends at the location of the "Proton Interrogation Target" shown by the green box in Fig. 1.

The knowledge of the beam parameters ($\alpha_{x,y}$, $\beta_{x,y}$) and the beam dispersion functions ($\eta_{x,y}$, $\eta'_{x,y}$) at the location of the "G10_kicker" are required, for the transport and focusing of the beam at the targets. The procedure to calculate these beam parameters and the dispersion functions are discussed in details in Refs. [2,3].

In this technical note we present the values of the beam parameters and dispersion functions for three extraction setups of the AGS. Using these beam parameters, we calculate the magnet settings of the beam transport line (yellow line in Fig. 1), which is comprised of the U_line section of the AtR line, followed by the "Z_line".

The "Z_line" is a continuation of the U_line and in this write up consists of three quadrupoles, the UQ14, UQ15 and UQ16 followed by a ~10 [m] or ~110 [m] drift space, depending on the location of the experimental target, which may be located at the "Cross-Section Target Wheel 1" or the " Proton Interrogation Target" respectively.

The UQ16 quadrupole is located ~22 [m] downstream of the WD1 magnet which is not used in the beam transport and it is purposely removed from the beam line because it acts as a limiting vertical aperture for the beam. It is understood that the transported beam should satisfy the required beam constraints along the line, as well as the required focusing at the target, described in the text below.

Figure 1. An aerial view of the Collider Accelerator Complex. The proton beam is pre accelerated by the TANDEM or LINAC, subsequently, it is injected into the Booster (red circle) for further acceleration, followed by beam injection in the AGS (yellow circle) for the final acceleration to 4 GeV. The beam transport line starts at the location of the "G10_kicker", ending at the location of "Proton interrogation target", with both locations, shown by green boxes.

Characteristics of the Extracted Beam

The proton beam will contain ~10^{11} protons of 4 GeV energy and will be delivered at the target in the form of a "single beam bunch" or "few bunches" ~50 nsec long with the all bunches arriving at the target in within few μsec. The corresponding momentum, γ, and βγ of each proton are p=4.848 GeV/c , γ=5.263, βγ=5.167. During the actual beam delivery, the projected beam emittances $\varepsilon_{x,y}$ (95% Normalized) are expected to be smaller than 20π[mm.mrad]. In this technical note we will assume that the projected beam emittances are equal to 20π[mm.mrad].

Brief description of the FEB process.

The steps for the FEB process are described below.

1. While the beam bunch/bunches is/are circulating in the AGS at 4 GeV, two local beam bumps are excited; one local bump, the "G10_bump", displaces the beam inside the C_shaped G10_kicker, and the other local bump, the "H10_bump", displaces the beam near the extraction septum "H10_septum". The location of the "G10_kicker" and the "H10_septum" in reference to the AGS ring are shown in Fig. 1 and also Fig 2. The green line in Fig. 2 shows a section of the circulating beam in AGS with the "G10_bump" and the "H10_bump" both excited.
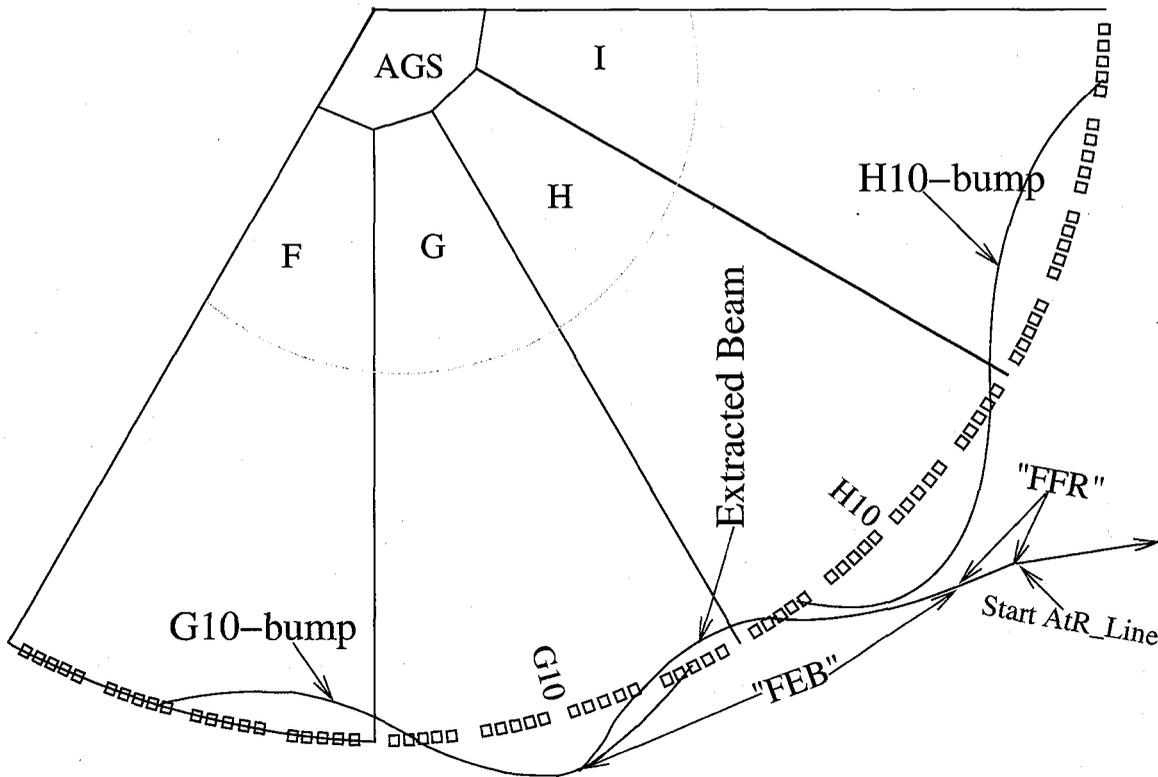

Figure 2: Diagram of the FEB section in AGS. The small blue squares are the AGS main magnets, the green lines, each correspond to the "G10" and "H10" local beam bumps (see text). The red line indicates the extracted beam trajectory after the G10_kicker fires.

2. With the local beam extraction bumps excited the G10_kicker is excited in ~100 nsec, to the require field, to kick only a single beam bunch by ~1.7 mrad, and further displace the beam into the main field region of the H10_septum which deflects the beam by ~20 mrad into the U_line which is the first section of the (AGS to RHIC) AtR transfer line. The trajectory of the extracted beam is shown in Fig. 2 by the red line.

3.

A detailed description of the extraction process is given in Refs [2,3,4].

Brief Description of the Beam Transport line

The transport of the extracted beam, to the target, begins at the location of the G10_kicker which kicks the beam by ~1.7 [mrad]. The trajectory of the extracted beam is shown schematically in Fig 2 by the red line.

For convenience we have divided the beam transport line of the extracted beam in three sections [3] shown in Fig. 2; namely the "FEB_section", which starts at G10_kicker and ends at the H10_septum, the "FFR_section" which starts at the H10_septum, passes by the fringe field of the H11,H12,and H13 AGS main magnets, and ends at the beginning of the AtR line, with the last section being the AtR line or any part of the AtR line.

In this technical note the third section of the beam transport line is comprised by the U_line followed by the "Z_line" which is described in the earlier section.

Beam Parameters used in the Transport of the Extracted Beam as Calculated using the "BEAM++" computer code for the AGS.

In this technical note we describe the optics of the beam transport from the beginning of the AtR line to the location of the "Cross-Section Target Wheel 1" and the location of the "Proton Interrogation Target". The beam parameters required for each of the beam transports are presented in Table 1. Three sets of such beam parameters are presented in Table 1, each set corresponding to a particular setting of the AGS at extraction, and is explained below.

- extraction setting #1:   The AGS is bare; both, the tune quadrupoles and the chromaticity sextupoles, are not excited.

- extraction setting #2:   Only tune quadrupoles are excited to set the horizontal and vertical tunes of the AGS at the values shown in Table 1 (column 4, 5). The chromaticity sextupoles are not excited.

- extraction setting #3:   The tune quadrupoles are excited to set the horizontal and vertical tunes of the AGS at almost the same values as in the extraction setting #2, These tunes are shown in Table 1 (column 4, 5). The chromaticity sextupoles are also excited to reduce the absolute value of the horizontal chromaticity shown in column 7.

Note (Table 1) that the horizontal and vertical tunes of the extraction settings #3 are set almost the same as the corresponding tunes of the extraction settings #2. This was done to

observe the effect of the chromaticity on the beam parameters and dispersion of the AGS.

By comparing the three extraction settings (Table 1), one can conclude on the dependence of the beam parameters at H13, "AGS extraction point", on the extraction settings of the AGS.

The rows 2 to 7 in Table 1 show the setup of the AGS at extraction. The values of the beam parameters ($\alpha_{x,y}$, $\beta_{x,y}$) and the beam dispersion functions ($\eta_{x,y}$, $\eta'_{x,y}$) of the extracted beam at the beginning of the transport line which is the "G10_kicker", and the beginning of the AtR line which is located at a distance of 450 [mm] from the middle of the H13 straight section of AGS, are presented in the remaining rows of Table 1.

Each of the last three columns corresponds to a particular setting of the AGS at extraction, (discussed above) and is indicated by the first seven rows of the Table 1.

In the process of calculating the beam parameters at the beginning of the AtR line, we obtain additional information described below:

a) The beam parameters ($\alpha_{x,y}$, $\beta_{x,y}$) and the beam dispersion functions ($\eta_{x,y}$, $\eta'_{x,y}$) at the starting location "G10_kicker" of the extracted beam.

b) The complete 6x6 "R transport matrix" from the G10_kicker to the H10_septum. This R_matrix describes the beam transport of the "FEB_section".

c) The complete 6x6 "R transport matrix" from the H10_septum, included, to the starting location of the AtR line (H13). This R_matrix describes the beam transport of the "FFR_section" therefore describes the beam focusing in the fringe field of the H11,H12, and H13 AGS main magnets.

d) The beam parameters ($\alpha_{x,y}$, $\beta_{x,y}$) and the beam dispersion functions ($\eta_{x,y}$, $\eta'_{x,y}$) at the starting location of the AtR line (H13).

The need for these results is described in Ref. [3] which also discusses details on the procedure to calculate the beam parameters at the beginning of the AtR line.

One of the conclusions from this brief study is that the beam parameters ($\alpha_{x,y}$, $\beta_{x,y}$) at the starting point of the AtR line (rows in Table 1 labeled H13) do not depend strongly on the tunes and chromaticities of the AGS synchrotron. Therefore we can vary the tunes and chromaticites in the AGS to satisfy beam stability of the circulating beam in AGS, without altering significantly the beam transport along the AtR line.

Table 1: The Calculated beam parameters and the dispersion functions of the extracted beam at the location G10 and H13, for three settings (see text) of the AGS at extraction. The beam parameters of the AGS and of the "FEB" section (see text) were calculated using the BEAM++ model of the AGS, as described in the text.

	Location	AGS_Settings#1	AGS_Settings#2	AGS_Settings#3
$B\rho$[Tm]	AGS	16.171	16.171	16.171
R_0[mm]	AGS	2.1	2.1	1.8
Q_x	AGS	8.726	8.786	8.782
Q_y	AGS	8.778	8.746	8.751
ξ_x	AGS	-17.7	-18.8	-10.8
ξ_y	AGS	+0.11	0.6	-4.3
β_x[m]	G10	16.670	15.838	16.549
α_x	G10	1.383	1.353	1.418
η_x[m]	G10	-1.445	-0.655	-1.163
η'_x	G10	0.158	0.002	0.054
β_y[m]	G10	14.44	15.281	15.031
α_y	G10	-1.237	-1.315	-1.295
η_y[m]	G10	0.0	0.0	0.0
η'_y	G10	0.0	0.0	0.0
β_x[m]	H13	33.577	32.725	31.797
α_x	H13	-3.563	-3.466	-3.553
η_x[m]	H13	-1.250	-0.869	-1.215
η'_x	H13	-0.086	-0.040	-0.0778
β_y[m]	H13	7.594	7.619	7.708
α_y	H13	1.058	1.059	1.156
η_y[m]	H13	0.0	0.0	0.0
η'_y	H13	0.0	0.0	0.0

Beam Optics of the Transported Beam and Tables with Values of the AtR Magnets.

In this section we present the optics of the transported beam from the beginning of the AtR line to the location of the "Cross-Section Target Wheel 1" and the "Proton Interrogation Target". We only present the optics of the beam transport that corresponds to the extracted beam settings#2, shown in Table 1.

The AtR magnet settings corresponding to all extraction settings, shown in Table 1 are tabulated in Table A1 of APPENDIX A. The magnet settings in Table A1 correspond to the product K1·L, where the symbol L is the length of the magnet, and K1 is the ratio of the gradient of the quadrupole, and the rigidity of the beam.

The optics of the beam transport should satisfy certain beam constraints including:

a) Beam spot at the "Cross-Section Target Wheel 1", should be 1 cm in radius. The beam spot includes one standard deviation of the beam intensity.

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b)   The beam spot on the " Proton Interrogation Target" is dominated by the effect of the multiple scattering of the beam (see following section) in the atmospheric air which exist in the drift space between the "Cross-Section Target Wheel 1" and the "Proton Interrogation target". However we will focus the beam at the "Proton Interrogation target" to the smallest possible spot assuming that the beam is transported in vacuum instead of air.

c)   The beam should be achromatic at the exit of the $8°$ bend.

d)   The beam should be focused to clear all limiting apertures of the transfer line. The main limiting apertures of the transport line are:

     d.1)   The vertical gap (22 mm) of the G10_kicker. The size of a beam with 95% Normalized emittance at the location of G10 kicker ($\beta_y \sim 20$ [m]) is ~0.9 cm, and this size includes 99% of the beam's intensity.

     d.2)   The Vertical gap of the $4°$ bend. (3.85 cm)

     d.3)   The Radius (r=3.8 cm) of the Q1 and Q2 quadrupoles

     d.4)   The gap of the $8°$ bend (3.9 cm)

Figure 3 shows the horizontal and the vertical beam profiles along the transport line starting from the beginning of the AtR line, and ending to the "Cross-Section Target Wheel 1". Each of the profiles contains 99% of the beam intensity.
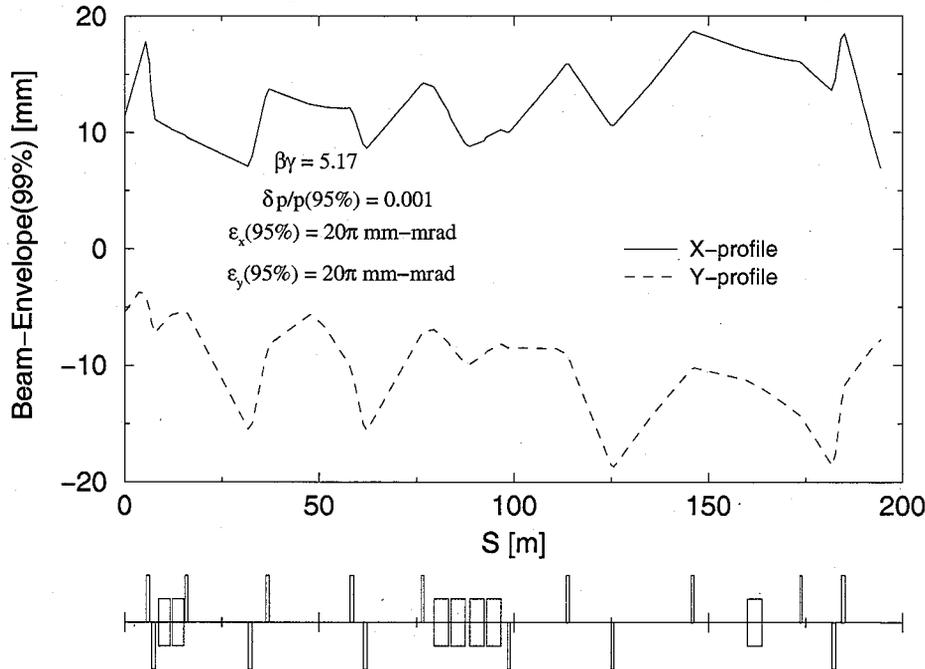

Figure 3. The horizontal beam profile (black line) and the vertical beam profile (red line) for the beam transport of T=4 GeV proton beam to the "Cross-Section Target Wheel 1". The assumed projected beam emittances $\varepsilon_{x,y}$ are 20 π[mm.mrad] 95% normalized. The momentum spread $\delta p/p$ of the beam is assumed to be 10^{-3}. The green boxes at the bottom of the picture are the dipoles and quadrupoles of the line.

The beam profiles shown in Fig. 3 were computed from the values of the beam parameters and dispersion functions along the line, shown in Fig. 4, using the projected beam emittances of $\varepsilon_x=\varepsilon_y=20\ \pi$[mm.mrad] 95% normalized, and a beam momentum spread of $\delta p/p=0.001$.
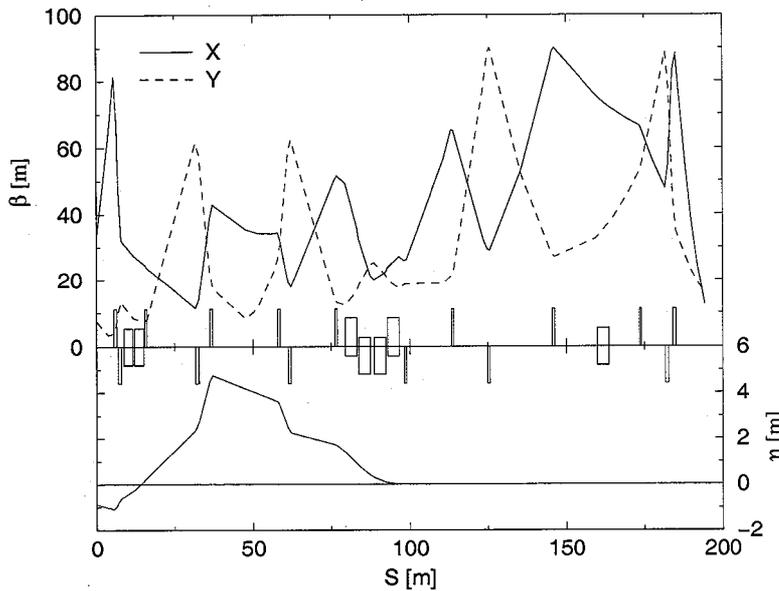

Figure 4. The beam parameters and the dispersion functions for the beam transport of T=4 GeV proton beam to the "Cross-Section Target Wheel 1". These data is used to calculate the beam profiles along the beam line, shown in Fig. 3.
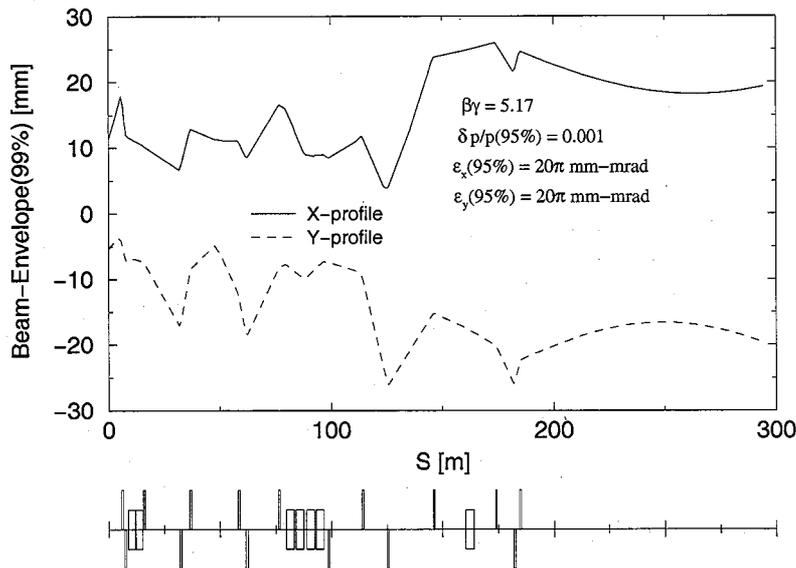

Figure 5. The horizontal beam profile (black line) and the vertical beam profile (red line) for the beam transport of T=4 GeV proton beam to the "Interrogation_Target". The assumed projected beam emittances $\varepsilon_{x,y}$ are 20 π[mm.mrad] 95% normalized. The green boxes at the bottom of the picture are the dipoles and quadrupoles of the line.

Figure 5 above shows the horizontal and the vertical beam profiles along the transport line starting from the beginning of the AtR line, ending to the "Proton Interogation Target". Each of the profiles contains 99% of the beam's intensity.

The beam profiles shown in Fig. 5 were computed from the values of the beam parameters and dispersion functions along the line, shown in Fig. 6 below, using a projected beam emittance $\varepsilon_x = \varepsilon_y = 20$ π[mm.mrad] 95% normalized, and a beam momentum spread of $\delta p/p = 0.001$.
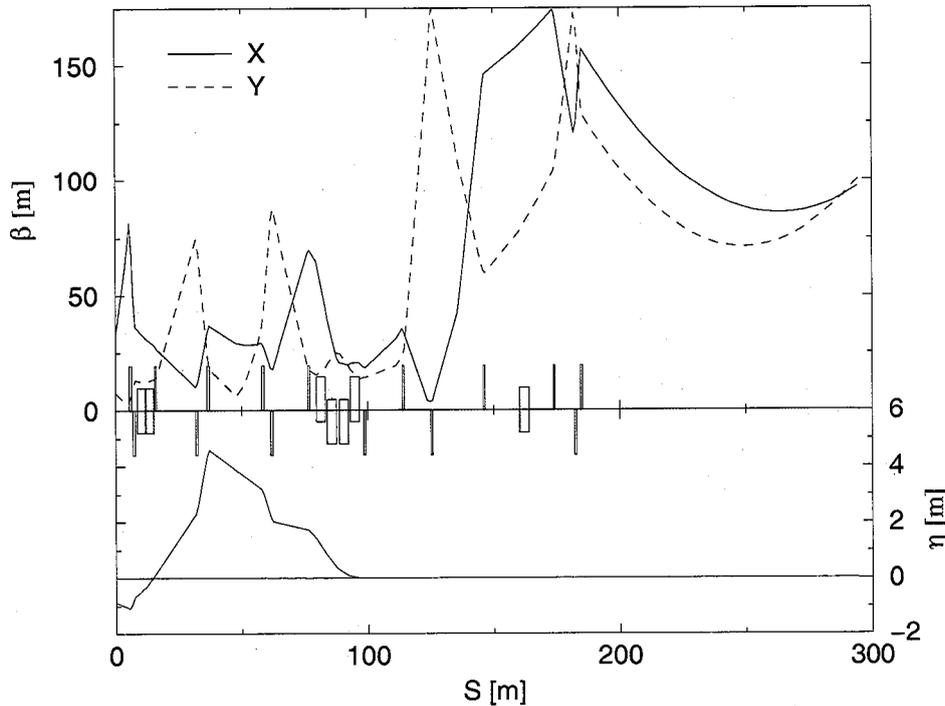

Figure 6. The beam parameters and the dispersion functions for the beam transport of T=4 GeV proton beam to the "Proton Interogation Target". These data is used to calculate the beam profiles along the line, shown in Fig. 5.

The magnet settings of each of the beam transport discussed in this technical note appear in the APPENDIX A.

Measurements that will benefit the AGS model

1. Measure the projected beam emittances of the circulating beam at extraction using the AGS IPM.

2. Measure the tunes, the chromaticities and dispersion function of the AGS at various settings of the AGS at extraction.

3. Compare results with the predictions of various models.

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4. Measure the projected beam emittance and beam parameters using the Visual Flags of the U_line and W_line.

Some of the proposed measurements above, have been performed in the year 2000 and the results appear in Ref. [5]

Effect of the Air on the Size of the Transported Beam

The size of the beam which includes 99% of its intensity at the " Proton Interrogation Target" is ~4 cm (see Fig. 5), in diameter. This assumes that the beam is transported in vacuum.
As we mentioned earlier the section of the beam transport line starting from the "Cross-Section Target Wheel 1", and ending at the "Proton Interrogation Target", is a drift space of ~100 [m] filled with atmospheric air in which the beam multiple scatters.
The effect of the air on the size of the beam has been calculated using two computer codes.

A computer code from "CERN" [6].
Using this code we calculate the beam size at two location; one location, at the "Proton Interrogation Target" which is 100 [m] downstream from the "Cross-Section Target Wheel 1", and the other location, half way to the "Proton Interrogation Target" (50 [m]).
In the calculations we use 20000 particles randomly selected from the beam ellipse at the point where the beam enters the atmospheric air. Each particle is randomly scattered by the air molecules on its way to the target and a new angle-coordinate of the particle is calculated after each random collision.

The horizontal (x) and vertical (y) beam profiles at the two locations mentioned above are shown in Fig. 7 . The values of the quantities $\sigma_{x,y}$ of the beam profiles are shown on the figure 7.
The beam distributions at the two locations (middle=>Red, Inter.Targt.=>Green/Black) are shown in Fig. 8.
Table 2 , in conjunction with Fig. 7 and Fig. 8 summarizes the results of the calculations.

Table 2. Information on the Beam Profiles and Beam Distributions at two locations along the beam.

Location	Condition	Beam Prof.	$\sigma_{x,y}$ [xm]	Beam Distr.	
Inter. Target	Vacuum	Fig. 7	0.8	Fig. 8 Green	
Inter. Target	Air	Fig. 7	8.4	Fig. 8 Black	
Half Way	Air	Fig. 7	3.0	Fig. 8 Red	

The results of the calculations proved that the beam size at the location of the "Proton Interogation Target" is "almost" independent of the starting beam distribution which is located at the "Cross-Section Target Wheel 1". For example a pencil like beam, {all 20000 particles used in the calculations, initiate at the same coordinate (x,x′, y,y′)=(0,0,0,0)}, yields "almost" the same beam profiles, as the beam which initiates
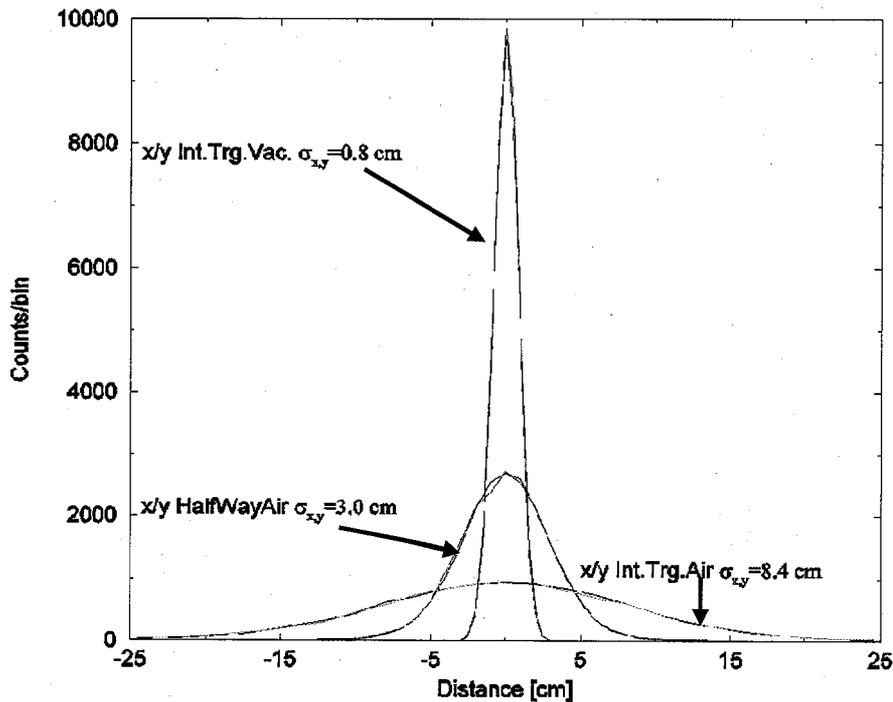
Figure 7. Horizontal and Vertical beam profiles at the location of the "Proton Interrogation Target" and half way to the "Proton Interrogation Target". The values of the standard deviations ($\sigma_{x,y}$) of the beam profiles are shown on the figure.
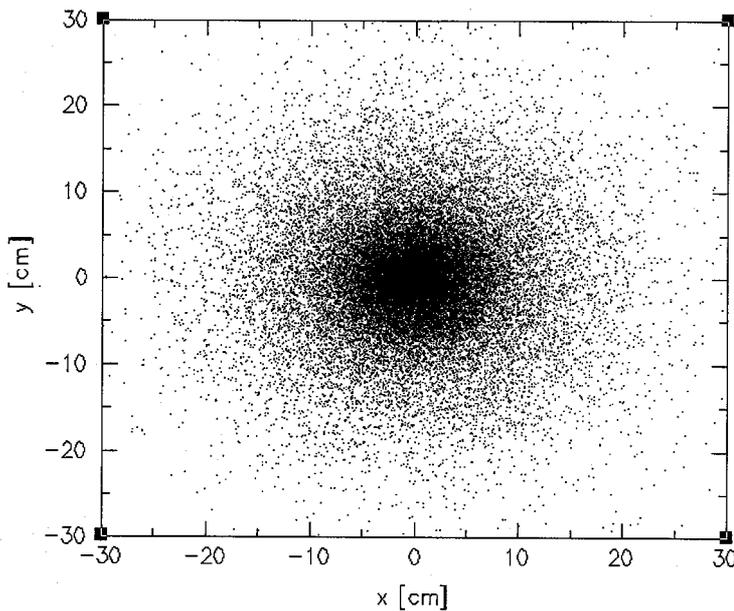

Figure 8. The beam distributions (Black and Green dots) at the "Proton Interrogation Target" , with air and vacuum in the drift space respectively. The red dots is the beam distribution half way when air is present.

from a Gaussian distribution, that is used to obtain the beam distributions and beam profiles shown in Figs. 7 and 8. This is expected since the multiple scattering on the beam

generates a much larger beam distribution at the "Interrogation Target" as compared to the beam distribution which is not affected by the air (in vacuum).

The next section provides an alternative beam focusing along the transport line. This focusing minimizes the vertical beam size of the beam at the location of the WD1 dipole magnet, thus minimizing the beam losses, if any, at this location, and allowing the WD1 magnet to stay put. In addition this section presents results of the beam size at the location of the "Proton Interrogation Target" when air is present in the last 100 m of the transport line. In these calculations the "TUTLE" computer code[7] was used than the one mentioned in the previous section .

Transport and Turtle simulations of the DTRA beam

The computer program Turtle [7] was used to predict the spread of the DTRA beam due to scattering in the vacuum window and air. The procedure followed is described below: The start point was the same as the previous MAD calculation with the input phase space taken from Table 1, AGS_Settings#2 at the H13 location. The MAD input beam parameters were converted to Transport [8] style input phase space for a 4 GeV proton beam with 20πmmmmr normalized emittance at 6 sigma (95%): Table 3 shows the converted MAD input beam parameters to Transport input beam phase space for various sizes of beam phase space.

Table 3. Transport input beam phase space, convereted from MAD AGS_Settings#2

	6 sigma (95%)	8.5 sigma (99%)	1 sigma (32%)	
x	1.125	1.339	0.459	cm
theta	1.24	1.476	0.506	mr
y	0.543	0.646	0.222	cm
phi	1.038	1.235	0.424	mr
dp/p	0.1	0.1	0.1	%
r12	0.961	0.961	0.961	cm/mr
r34	-0.727	-0.727	-0.727	cm/mr
r16	-0.869	-0.869	-0.869	cm/%
r26	-0.40	-0.40	-0.40	mr/%
Emittance (absolute)	3.87	5.48	0.645	π[mm.mrad]

The Transport fit was not sophisticated, fixing UQ6 at zero field and allowing the remaining quadrupoles fields and polarities to vary. The fit was done in two steps, first a zero dispersion tune was developed downstream of the 8 degree bend then the remainder of the beam line was fit. The constraints included:

- Zero beam dispersion downstream of the 8 degree bend

- The 99% beam envelope was constrained to be less than 60-70 % of the full magnet apertures and

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- The beam size at the "Proton Interrogation Target" (TGT2) was minimized (fit to "0" cm)

The WD1 RHIC dipole was left in place for this exercise with assumed horizontal and vertical aperture limits of ±27mm and ±15 mm respectively. The results are shown in Figure 8. This result is similar to that of Tsoupas et. al. [9] for a tune developed, but never tried, for LANL Proton Radiography experiments. In this model losses at the 1 part in 10,000 level begin at about a positive x = 15 mm and y = ±6 mm at the exit of WD1 so there's contingency in this tune to get the beam through WD1 with minimal losses. The resulting quadrupole settings for a 4 GeV proton beam are given in Table 4 below. This tune requires polarity reversals for UQ10 through UQ14, none of which have polarity reversal switches. Except for UQ10 this was also the case for the tune developed in Ref 9. Manual polarity reversal requires much less effort and time than removing and reinstalling WD1 so this solution should be considered for the DTRA experiment, at least for proton beam energies above 3-4 GeV with 20πmmmr normalized emittance. The tune results in a beam size at the "Cross-Section Target Wheel 1" of about 1.1 cm (1 sigma) for both x and y so this tune may also work for targets at that location.

Table 4. Transport quadrupole parameters for the fit described above.

Element	Effective length (meters)	Radius (cm)	Pole Tip field (Kg)
UQ1	0.953	3.81	2.336
UQ2	0.953	3.81	-2.606
UQ3	0.726	5.08	1.254
UQ4	1.000	5.08	-1.520
UQ5	1.000	5.08	1.698
UQ6	0.740	5.08	0
UQ7	1.000	5.08	2.286
UQ8	1.000	5.08	-1.825
UQ9	0.726	5.08	2.292
UQ10	0.740	5.08	0.641
UQ11	0.740	5.08	-0.758
UQ12	0.740	5.08	0.759
UQ13	0.740	5.08	-0.920
UQ14	0.457	5.08	0.258
UQ15	0.947	6.35	-1.834
UQ16	0.947	6.35	1.544

This transport tune was then used as input to the Turtle beam simulation program. Turtle allows tracing of individual rays through all elements as well as coulomb multiple scattering, nuclear elastic scattering and absorption (REVMOC routine, Ref 10). The model includes a 10 mil aluminum U-line vacuum window located 8.1 meters downstream of the UQ16 centerline followed by 100 meters of air to the "Proton

Interrogation Target" (TGT2) location. The input file is given in Appendix B. and some of the results are shown in Figures 9-21.

- Figures 9 and 10 show the Turtle x vs theta and y vs. phi input phase.

- Figures 10 and 11 show the horizontal and vertical beam profiles at the exit of WD1.

- Figures 12 and 13 show the horizontal and vertical beam profiles at the location of the "Proton Interrogation Target" when the beam is transported in vacuum.

- Figures 14-18 show the horizontal and vertical beam profiles at the location of the "Proton Interrogation Target" when the transported beam is in air in the last 100 meters. The effect of the aluminum window (small) which separates the vacuum from the air is included in the calculations. Note that Figures 17 and 18 are log plots and one can see the long tails caused by nuclear elastic scattering.

- Figure 19 shows the beam losses occurring in the various apertures of the beam line as well as interaction losses in the vacuum window and 100 meters of air.
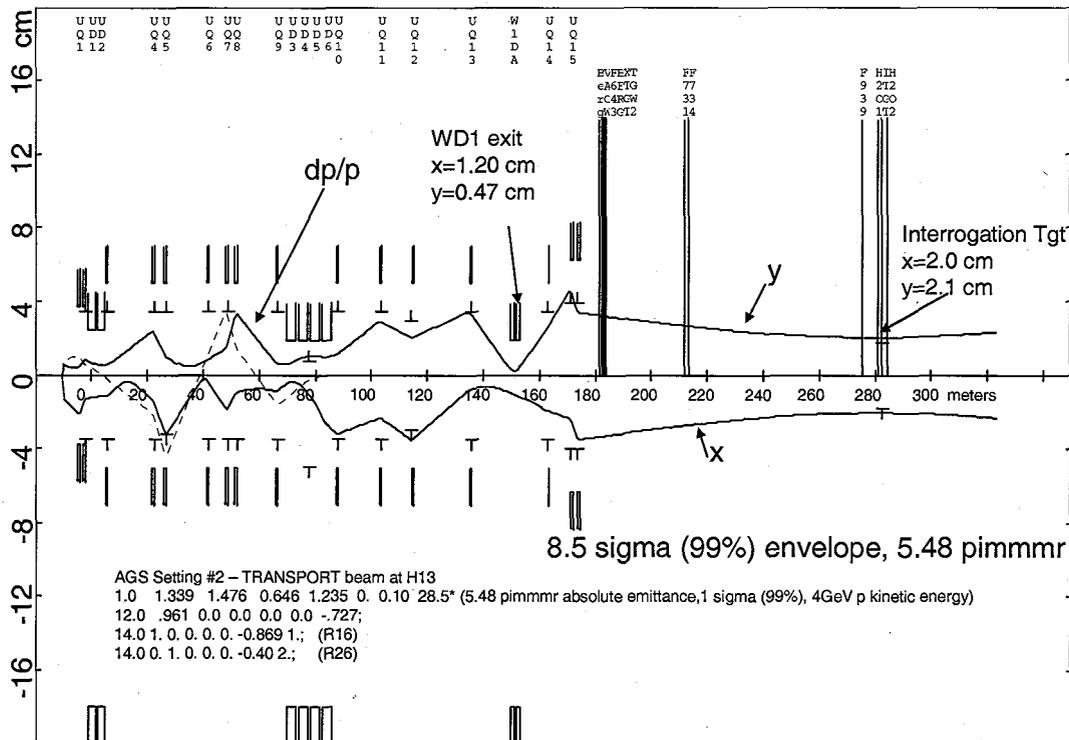

Figure 8. The Transport 99% beam envelope for a minimum beam size at "Proton Interrogation Target" – first order with no multiple scattering.
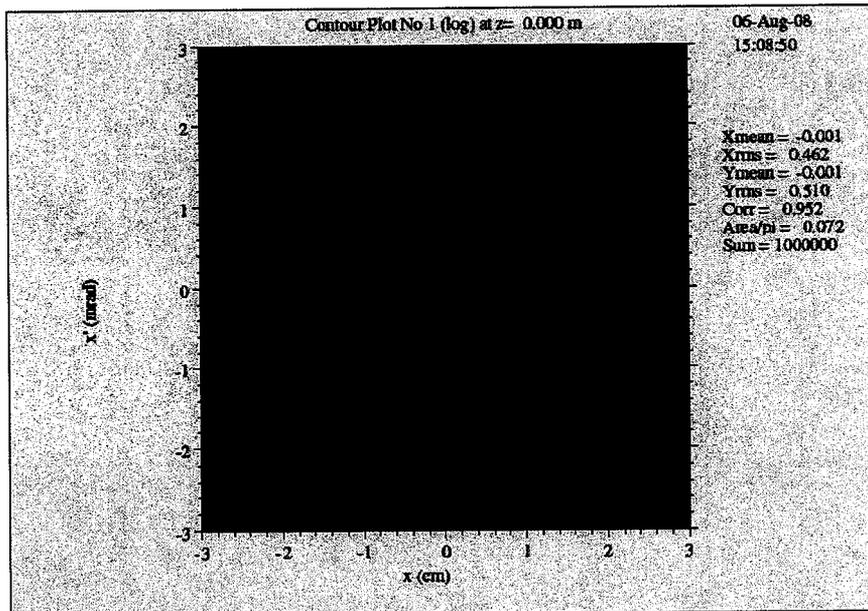
Figure 9 Input x vs. theta phase space for 4 GeV proton
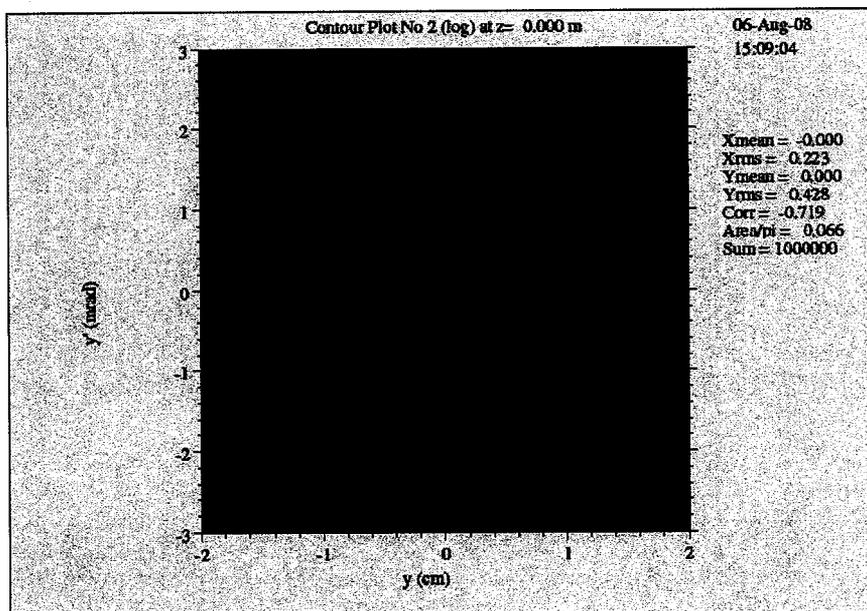

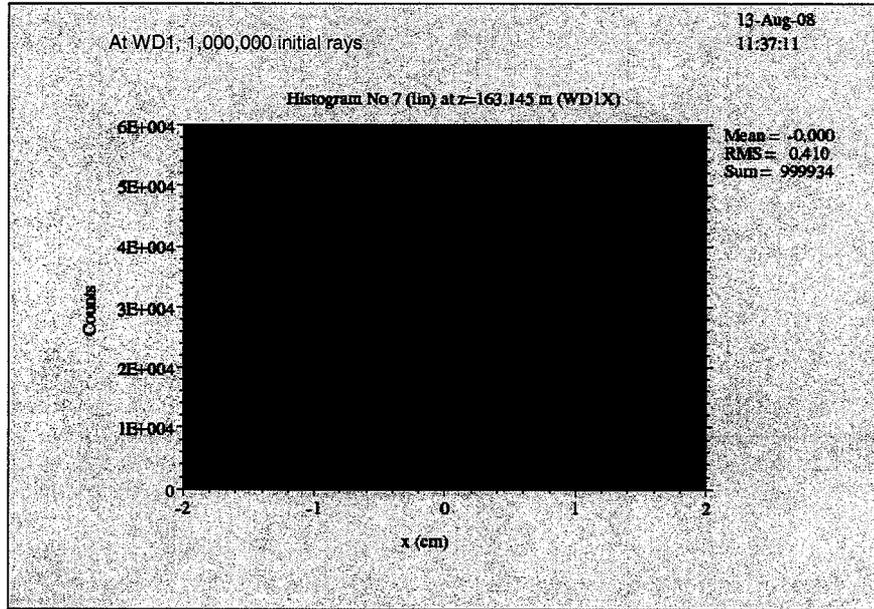Figure 10. Input y vs. phi phase space for 4 GeV proton
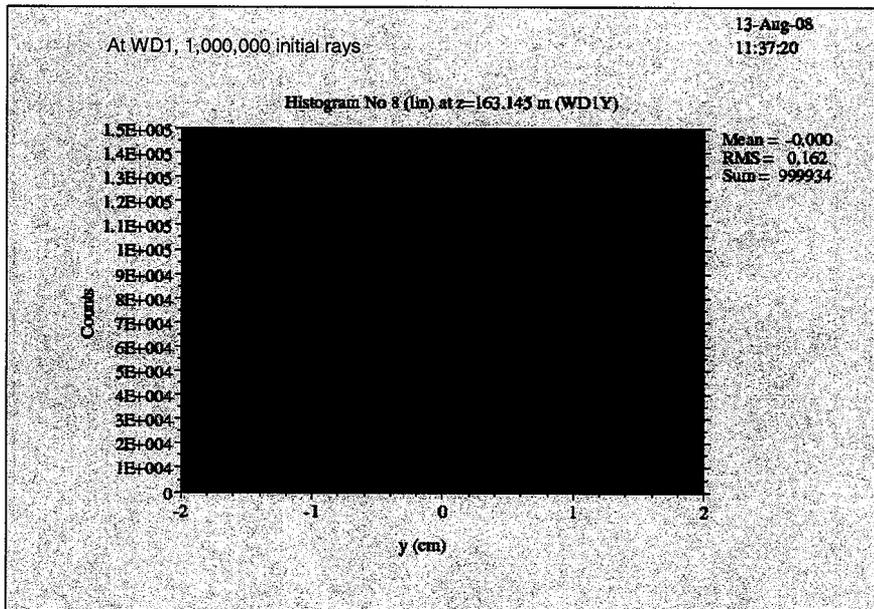
Figure 11. x distribution at exit of WD1.

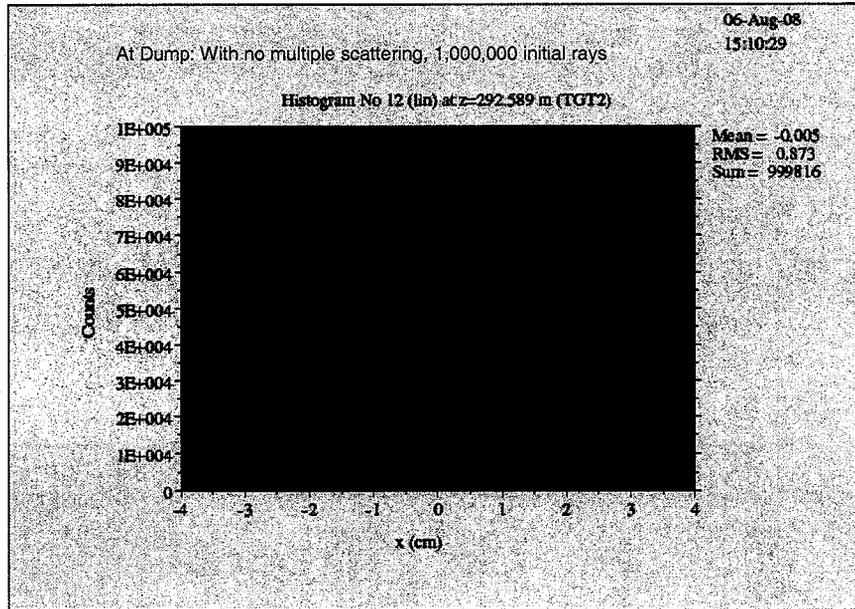Figure 12. y distribution at exit of WD1.

Figure 13. x distribution at "Proton Interrogation Target" with no multiple scattering or absorption
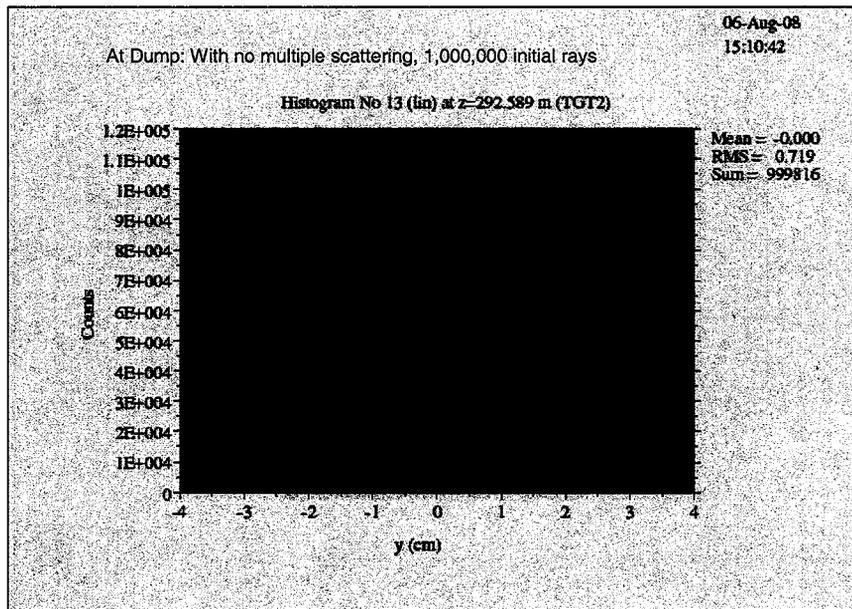

Figure 14. y distribution at "Proton Interrogation Target" with no multiple scattering or absorption

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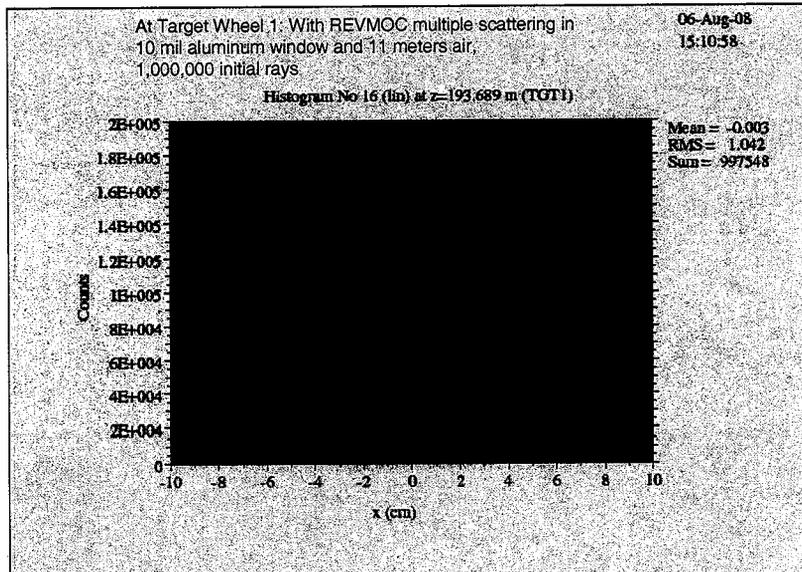Figure 15. x distribution at target 1 ("Cross-Section Target Wheel 1" position) with scattering and absorption.
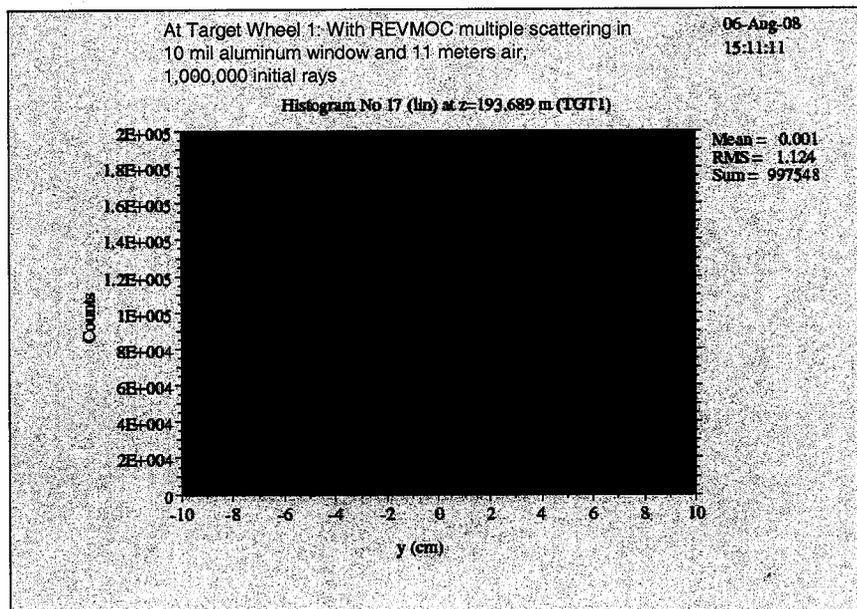

Figure 16. y distribution at target wheel 1 ("Cross-Section Target Wheel 1" position) with scattering and absorption.
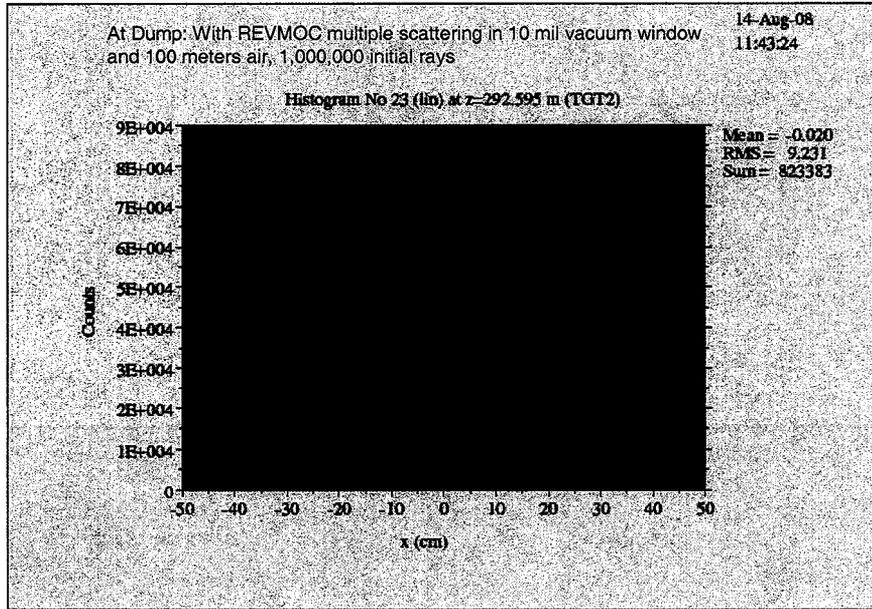
Figure 17. x distribution at "Proton Interrogation Target" with scattering and absorption
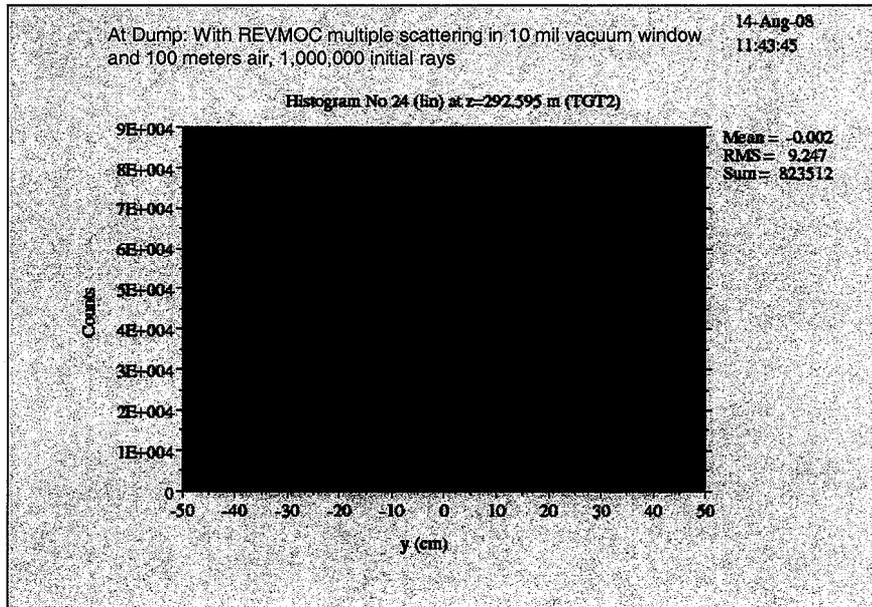
Figure 18. y distribution at "Proton Interrogation Target" with scattering and absorption

At Dump: With REVMOC multiple scattering in 10 mil vacuum window   06-Aug-08 15:11:58
and 100 meters air, 1,000,000 initial rays

Histogram No 29 (log) at z=292.595 m (TGT2)

Mean = -0.010
RMS = 36.558
Sum = 863374

x (cm)

Figure 19. x distribution at "Proton Interrogation Target" with coulomb and nuclear
scattering and absorption – log plot

At Dump: With REVMOC multiple scattering in 10 mil vacuum window   06-Aug-08 15:12:10
and 100 meters air, 1,000,000 initial rays

Histogram No 30 (log) at z=292.595 m (TGT2)

Mean = -0.002
RMS = 36.353
Sum = 863374

y (cm)
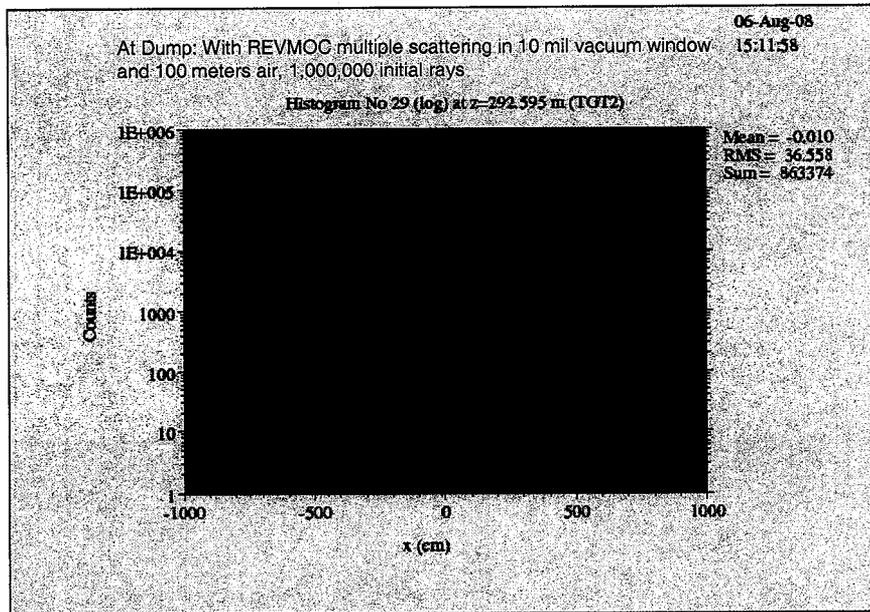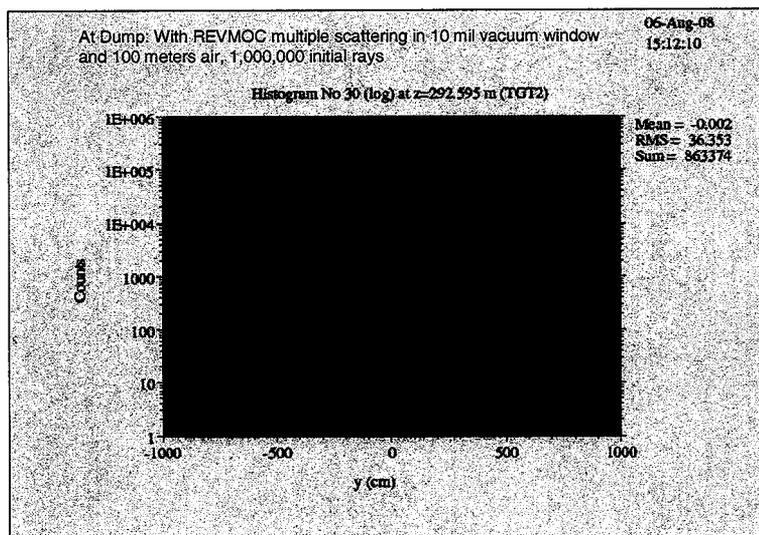
Figure 20. y distribution at "Proton Interrogation Target" with coulomb and nuclear
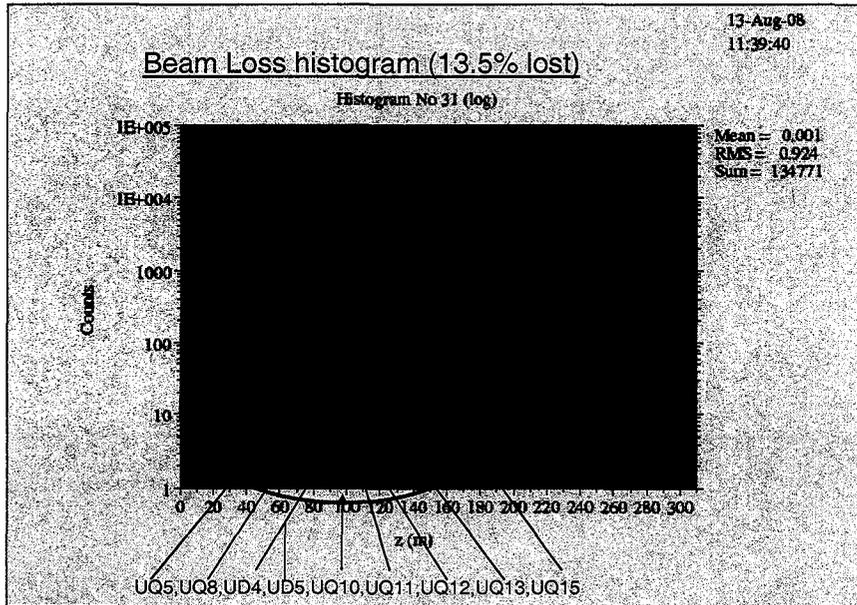scattering and absorption – log plot

Figure 21. Beam loss histogram

Beam Transport, Using a MAD-model of the U-Z_line, with WD1 Dipole Magnet not removed

This section, is very similar to the previous section, which uses the TURTLE computer code[7] to model the beam line, and also assumes that the WD1 magnet is not removed, but this section uses a MAD-model for the beam transport line, and also provides the values of K1*L which are required by the "AtR magnet" application. These values are shown in Table 5.

Figure 22a and 22b show the horizontal and vertical beam profiles, which correspond to the beam transports shown in Figs. 23a and 23b.
Note in these Figures 22a and 22b, the vertical beam profile at the location of the WD1 (vertical blue lines) is ~13 mm. The gap of the WD1 magnet is ~35 mm.
The calculation of the beam profiles were based on the values $\varepsilon_{x,y}$ (95% Normalized) = 20π[mm.mrad] and $\delta p/p=0.001$.

Figure 22a. The horizontal and vertical beam profiles along the beam transport line to the "Cross-Section Target Wheel 1". These beam profiles, which contain 99% of the beam's intensity, have been calculated using the beam parameters and dispersion function, shown in Fig. 23 a. Note the vertical beam profile at the location of the WD1 (vertical blue lines) is ~13 mm. The gap of the WD1 magnet is ~35 mm.
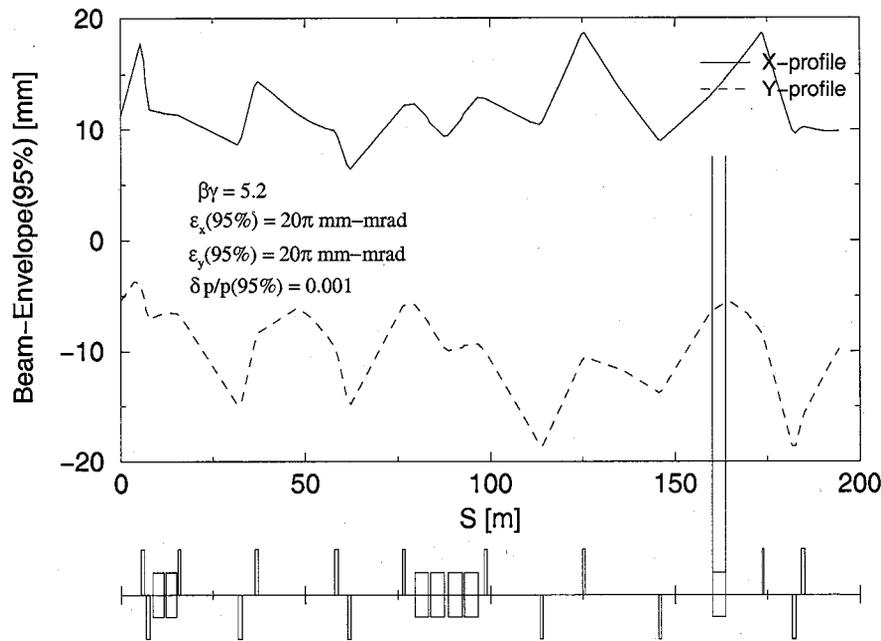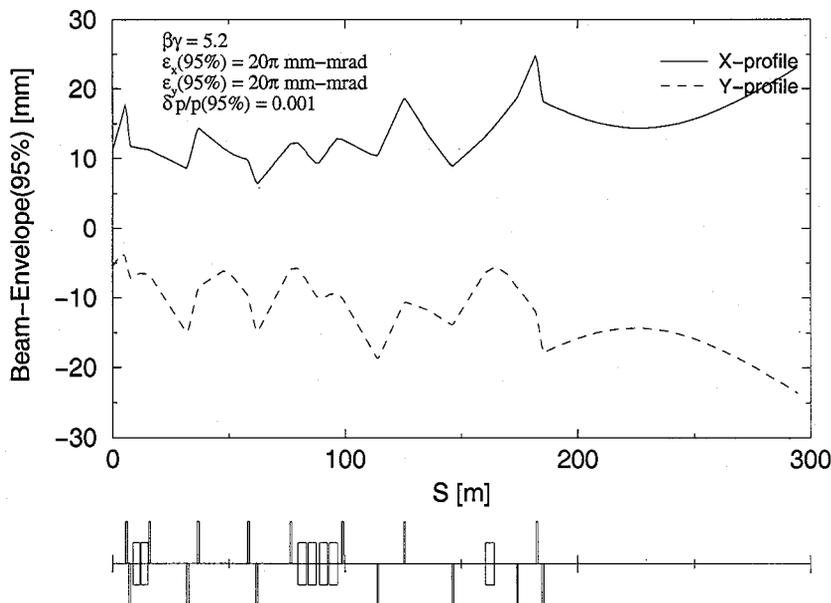

Figure 22b. The horizontal and vertical beam profiles along the beam transport line to the "Proton Interrogation Target". These beam profiles, which contain 99% of the beam's intensity, have been calculated using the beam parameters and dispersion function, shown in Fig. 23b. Like in Fig. 22a the vertical beam profile at the location of the WD1 is ~13 mm.

Figure 23a and 23b show the horizontal and vertical beta functions and the dispersion function along the transport lines which ends at the location of the "Cross-Section Target Wheel 1" and the "Proton Interrogation Target" respectively.

Figure 23a. The horizontal and vertical beta functions and the dispersion function along the beam line to the "Cross-Section Target Wheel 1".

Figure 23a. The horizontal and vertical beta functions and the dispersion function along the beam line to the "Cross-Section Target Wheel 1".

Beam Parameters of the Extracted Beam as Calculated using the MAD-model for the AGS ring.

This section is similar to an early section, which uses the BEAM++ based model of the AGS [3,11], to calculates the beam parameters at the beginning of the AtR line, bu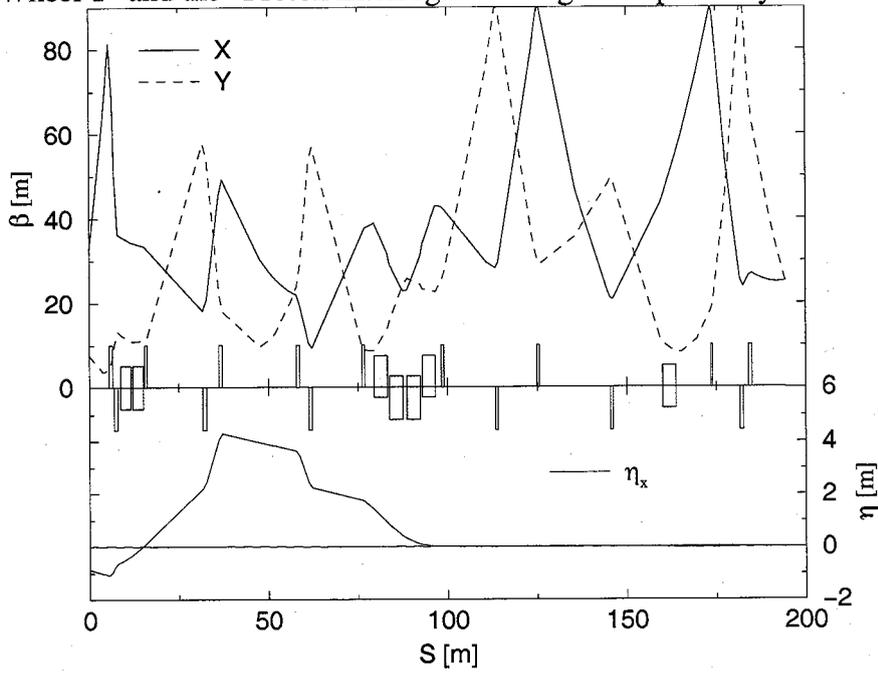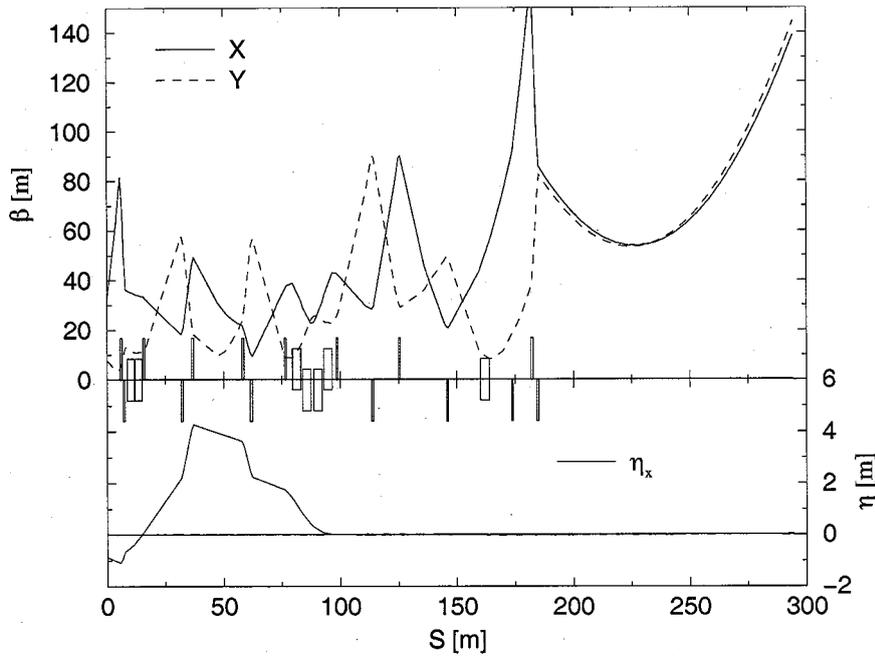t in this section we utilize a MAD-model of the AGS, to calculate these beam parameters. In this section we simply report the calculated beam parameters which appear in Table 5. This Table corresponding to the Table 1 of the earlier section. Although we only use the results appearing in Table 1 for the beam transport, we report these results to compare the two models, the BEAM++ and MAD model of the AGS.

Table 5: The Calculated beam parameters and the dispersion functions of the extracted beam at the location G10 and H13, for three settings (see text) of the AGS at extraction. The beam parameters of the AGS and of the "FEB" section (see text) were calculated using a MAD-model of the AGS.

	Location	AGS_Settings#1	AGS_Settings#2	AGS_Settings#3
$B\rho[Tm]$	AGS	16.171	16.171	16.171
$R_0[mm]$	AGS	-1.96	-1.96	-1.58
Q_x	AGS	8.684	8.787	8.783
Q_y	AGS	8.771	8.746	8.750
ξ_x	AGS	-20.7	-20.2	-10.3
ξ_y	AGS	+1.1	0.9	-4.3
$\beta_x[m]$	G10	16.769	16.345	17.377
α_x	G10	1.368	1.443	1.522
$\eta_x[m]$	G10	-1.294	-0.429	-1.178
η'_x	G10	+0.141	-0.040	+0.046
$\beta_y[m]$	G10	14.403	15.679	15.202
α_y	G10	-1.205	-1.412	-1.374
$\eta_y[m]$	G10	0.0	0.0	0.0
η'_y	G10	0.0	0.0	0.0
$\beta_x[m]$	H13	33.157	30.855	32.758
α_x	H13	-3.526	-3.268	-3.381
$\eta_x[m]$	H13	-0.943	-0.114	-1.315
η'_x	H13	-0.059	+0.044	-0.105
$\beta_y[m]$	H13	7.502	7.768	7.917
α_y	H13	1.069	1.100	1.232
$\eta_y[m]$	H13	0.0	0.0	0.0
η'_y	H13	0.0	0.0	0.0

Conclusions

We have calculated the optics of the beam transport from the AGS to the "Cross-Section Target Wheel 1" and to the "Proton Interrogation Target".
Two beam transports have been calculated; one which requires that the WD1 dipole magnet is removed from its present location, and the other, which does not require the removal of the WD1 magnet.
The AtR magnet settings for the two beam transports have also been tabulated.
We have also calculated the beam sizes at the location of the "Proton Interrogation Target" as it is affected by the atmospheric air which exists at the last 100 [m] of drift space of the line.

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[8] PSI Graphic Transport Framework by U. Rohrer based on a CERN-SLAC-FERMILAB version by K.L. Brown et al.
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[10] C. Kost, P. Reeve: REVMOC - A Monte Carlo Beam Transport Program, TRI-DN-82-28 (1983).
[11] **N. Tsoupas, et. al. "R-MATRICES OF THE FAST BEAM EXTRACTION LINE OF AGS"** Jenoa, Italy, EPAC June 2008

APPENDIX A

Magnet settings of the U_line and Z_line for each of the three sets of beam parameters discussed in this technical Note.

Table A1 shows the settings of the Quadrupoles of the U_line and Z_line for the beam transport to the "Cross-Section Target Wheel 1" .

Table A1: The Quadrupoles settings of the U_line and Z_line for the beam transport to the "Cross-Section Target Wheel 1" .

	Xtr_set#1		Xtr_set#2		Xtr_set#3	
Quad	K1 [m^{-2}]	K1*L [m^{-1}]	K1 [m^{-2}]	K1*L [m^{-1}]	K1 [m^{-2}]	K1*L [m^{-1}]
UQ1	0.356862	0.33991129	0.371079	0.35345277	0.357195	0.3402285
UQ2	-0.38018	-0.3621255	-0.40951	-0.3900620	-0.38585	-0.367526
UQ3	0.084985	0.06173647	0.051212	0.03720246	0.093117	0.0676436
UQ4	-0.15516	-0.1551591	-0.15573	-0.1557255	-0.15324	-0.153244
UQ5	0.127887	0.12788727	0.123937	0.12393734	0.1251207	0.12512070
UQ6	0.0	0.0	0.0	0.0	0.0	0.0
UQ7	0.089508	0.08950824	0.089685	0.08968535	0.094633	0.0946330
UQ8	-0.15172	-0.1517238	-0.14387	-0.1438721	-0.15387	-0.153870
UQ9	0.063767	0.04632280	0.058131	0.04222902	0.060082	0.0436461
UQ10	-0.08669	-0.0629715	-0.06141	-0.0446136	-0.07440	-0.054050
UQ11	0.111390	0.08242893	0.081828	0.06055293	0.099424	0.0735739
UQ12	-0.10732	-0.0794162	-0.09648	-0.0713919	-0.10346	-0.073574
UQ13	0.053012	0.03922853	0.041848	0.03096761	0.055183	0.0408356
UQ14	0.032796	0.01499440	0.037012	0.01692228	0.013308	0.0060843
UQ15	-0.20205	-0.1914279	-0.19749	-0.1871041	-0.19167	-0.181596
UQ16	0.209259	0.19825641	0.205485	0.19468078	0.221658	0.2100036

Table A2 shows the settings of the Quadrupoles of the U_line and Z_line for the beam transport to the "Interogation Target" .

Table A2: The Quadrupoles settings of the U_line and Z_line for the beam transport to the "Proton Interrogation Target" .

	Xtr_set#1		Xtr_set#2		Xtr_set#3	
Quad	K1 [m^{-2}]	K1*L [m^{-1}]	K1 [m^{-2}]	K1*L [m^{-1}]	K1 [m^{-2}]	K1*L [m^{-1}]
UQ1	0.356862	0.33991129	0.371079	0.35345277	0.357195	0.3402285
UQ2	-0.38018	-0.3621255	-0.40951	-0.3900620	-0.38585	-0.367526
UQ3	0.084985	0.06173647	0.051212	0.03720246	0.093117	0.0676436
UQ4	-0.15516	-0.1551591	-0.15573	-0.1557255	-0.15324	-0.153244
UQ5	0.127887	0.12788727	0.123937	0.12393734	0.1251207	0.12512070
UQ6	0.0	0.0	0.0	0.0	0.0	0.0
UQ7	0.089508	0.08950824	0.089685	0.08968535	0.094633	0.0946330

UQ8	-0.15172	-0.1517238	-0.14387	-0.1438721	-0.15387	-0.153870
UQ9	0.063767	0.04632280	0.058131	0.04222902	0.060082	0.0436461
UQ10	-0.08669	-0.0629715	-0.06141	-0.0446136	-0.07440	-0.054050
UQ11	0.111390	0.08242893	0.081828	0.06055293	0.099424	0.0735739
UQ12	-0.11003	-0.081421	-0.09956	-0.0736752	-0.10706	-0.079227
UQ13	0.119753	0.08861718	0.102506	0.0758541	0.118994	0.0880558
UQ14	0.00	0.00	0.00	0.00	0.00	0.00
UQ15	-0.13926	-0.1319364	-0.13999	-0.1326255	-0.13973	-0.132385
UQ16	0.142254	0.1347742	0.146103	0.13842042	0.142886	0.1353735

APPENDIX B

Turtle input file for alternate beam tune with WD1 in place.

" U-Line for DTRA page 96 for 4 GeV and 20 pimmmr norm 95% emit"
1000000
15. 11. /MeVc/ .001;
15. 12. /MeV/ .001;
1.0 0.918 1.012 0.444 0.848 0. 0.10 28500. * (0.645 pimmmr 32% pp 1 sigma,2 sigma
for Turtle input)
12.0   .961 0.0 0.0 0.0 0.0 -.727   *   (r12 and r34)
3. 0.;
14.0 1. 0. 0. 0. 0. -0.869 1.;   (R16)
14.0 0. 1. 0. 0. 0. -0.40 2.;   (R26)
3. 0.;
16. 3. 1836.7 /MASS/;   (proton mass in electron units)
51. 1. -3. 3. .1;
52. 2. -3. 3. .2;
51. 3. -2. 2. .05;
52. 4. -3. 3. .2;
17.0 ;   (2nd Order)
17.0 3. ;   (3rd Order)
3. 0.;
13. 10. ;   (Aperatures observed)
16. 190. 0. 100. /FILE/;   (Metafile for graphics = FOR001.DAT)
3. .004;
3. 0.46;
3. 2.5;
3. .2768;   (VKICK -UKS1)
3. 0.61;
3. .152;
3. .61;   (HKICK -UTH2)
3. .764;
5.0 0.9525 13.7242 3.81 "UQ1" *   ( )
3. .4953;
5.0 0.9525 -15.3135 3.81 "UQ2" *   ( )
3. .886;
16. 7. .45;
16. 8. 2.8;
16. 4. 7.62;
16. 5. 2.54;
2. 1.078;
4.0 2.947 12.159 10. "UD1"; (2.156 deg)
2. 1.078;
3. .45;

2. 1.078;
4.0 2.947 12.159 -10. "UD2"; (2.156 deg)
2. 1.078;
3. .395;
5.0 0.7264 7.3704 5.08 "UQ3" * ( )
3. 3.;
3. 3.;
3. 3.;
3. 6.5;
5.0 1.000 -8.9315 5.08 "UQ4" * ( )
3. 1.14;
3. 2.317;
5.0 1.000 9.9801 5.08 "UQ5" * ( )
3. 4.755;
3. 5.74;
3. 2.48;
3. .354;
3. .796;
5.0 0.74 -0.00 5.08 "UQ6" * ( )
3. 2.228;
3. 1.608;
3. .61; (HKICK)
3. .152;
3. .61; (VKICK)
3. .584;
5.0 1.000 13.4306 5.08 "UQ7" * ( )
3. 2.517;
5.0 1.000 -10.7259 5.08 "UQ8" * ( )
3. 1.821;
3. 4.;
3. 4.;
3. 4.;
5.0 0.7264 13.466 5.08 "UQ9" * ( )
3. 2.;
3. .676;
16. 7. .45;
16. 8. 2.8;
16. 4. 6.35;
16. 5. 1.8;
2. 1.0;
4.0 3.6576 9.07266 -206.67 "UD3" ; (2 deg)
2. 1.0;
3. .6096;
2. 1.0;
4.0 3.6576 9.07266 206.67 "UD4" ; (2 deg)
2. 1.0;

```
3. .6096;
2. 1.0;
10.2 1. 1. 5. .000001 "F1";
10.2 3. 3. .8 .000001 "F1";
4.0 3.6576 9.07266 206.67   "UD5" ; (2 deg)
2. 1.0;
3. .6096;
2. 1.0;
4.0 3.6576 9.07266 -206.67   "UD6" ; (2 deg)
2. 1.0;
3. 1.696;
5.0 0.72644 3.7695  5.08 "UQ10"  *      ()
3. 2.834;
3. 0.61;  (VKICK)
3. 1.081;
3. 9.902;
5.0 0.74 -4.4523  5.08 "UQ11"  *      ()
3. .712;
3. .61;  (HKICK)
3. 2.927;
3. 5.114;
3. 1.385;
5.0 .74 4.4629  5.08 "UQ12"  *      ()
3. .711;
3. .61;  (VKICK)
3. 8.159;
3. 9.649;
3. .7745;
5.0 0.74 -5.4058  5.08 "UQ13"  *      ()
3. 3.828;
3. 4.;
3. 4.627;
3. .744;
3. .625;
-16. 7. .45;
-16. 8. 2.8;
-16. 4. 8.25;
-16. 5. 1.5;
50. 1. -2. 2. .05 /WD1X/;
50. 3. -2. 2. .05 /WD1Y/;
6. 3. 1.5 /WD1Y/;
6. 1. 2.7 /WD1X/;
3. 1.829;                    (WD1)
-4.0 1.829 0.0001 0.  "W1DA" ; (0 deg)
50. 1. -2. 2. .05 /WD1/;
50. 3. -2. 2. .05 /WD1/;
```

```
6. 3. 1.5 /WD1Y/;
6. 1. 2.7 /WD1X/;
3. 1.829;
6. 3. 1.5 /WD1Y/;
6. 1. 2.7 /WD1X/;
-4.0 1.829 0.0001 0.   "W1DB" ; (0 deg)
50. 1. -3. 3. .05 /WD1X/;
50. 3. -3. 3. .05 /WD1Y/;
3. 4.265;
3. 1.5;
3. 4.0;
5.0 0.4572 1.5152  5.08 "UQ14"  *      ( )
3. 3.7456;
3. 4.0;
5.0 0.9474 -10.7765  6.35 "UQ15"  *      ( )
3. 1.473;
5.0 0.9474 9.0733 6.35 "UQ16"  *      ( )
3. 7.226 /Berg/;
3. 0.8824 /VACW/;
3. 100. "tgt";          (drift to tgt2 no multiple scattering)
51. 1. -4. 4. .2 /TGT2/;
52. 3. -4. 4. .4 /TGT2/;
51. 1. -4. 4. .2 /TGT2/;
52. 2. -1. 1. .1 /TGT2/;
51. 3. -4. 4. .2 /TGT2/;
52. 4. -1. 1. .1 /TGT2/;
50. 1. -4. 4. .2 /TGT2/;
50. 3. -4. 4. .2 /TGT2/;
3. -100. "tgt";          (back to vacuum window)
16. 165;               (enables REVMOC multiple scattering)
16. 160;               (inverse slit)
6. 1. 1000. 3. 1000.;
1. .153 9.07 22.56 0.566 16.5 .0226 0.1127 0. /Al/;  (10 mil Al window)
3. .000254;
51. 1. -10. 10. .5 /VACW/;
52. 3. -10. 10. 1. /VACW/;
3. 0. ;
16. 165;               (enables REVMOC multiple scattering)
16. 160;               (inverse slit)
9. 11.;                (drift in air to cross section target)
6. 1. 1000. 3. 1000.;
1. .044 7.07 42600. 0.613 20.3 .0044 0.0228 0. /AIR1/;  (based on 0.1 meter)
3. .1;
9. 0.;
3. 0 /TGT1/;          (cross section target)
51. 1. -10. 10. .5 /TGT1/;
```

```
52. 3. -10. 10. 1. /TGT1/;
50. 1. -10. 10. .5 /TGT1/;
50. 3. -10. 10. .5 /TGT1/;
16. 165;            (enables REVMOC multiple scattering)
16. 160;            (inverse slit)
9. 989.;            (drift through air to interrogation target)
6. 1. 1000. 3. 1000.;
1. .044 7.07 42600. 0.613 20.3 .0044 0.0228 0. /AIR2/;  (based on 0.1 meter)
3. .1;
9. 0. /TGT2/;
51. 1. -100. 100. 2.5 /TGT2/;
52. 3. -100. 100. 5. /TGT2/;
51. 1. -50. 50. 2.5 /TGT2/;
52. 2. -20. 20. 2. /TGT2/;
51. 3. -50. 50. 2.5 /TGT2/;
52. 4. -20. 20. 2. /TGT2/;
50. 1. -50. 50. 2. /TGT2/;
50. 3. -50. 50. 2. /TGT2/;
51. 1. -200. 200. 5. /TGT2/;
52. 3. -200. 200. 10. /TGT2/;
50. 1. -200. 200. 10. /TGT2/;
50. 3. -200. 200. 10. /TGT2/;
51. 1. -500. 500. 20. /TGT2/;
52. 3. -500. 500. 40. /TGT2/;
50. 1. -500. 500. 25. /TGT2/;
50. 3. -500. 500. 25. /TGT2/;
50. 1. -1000. 1000. 50. /TGT2/;
50. 3. -1000. 1000. 50. /TGT2/;
50. 8. 0. 310. 5. /LOSS/;
50. 8. 180. 310. 2. /LOSS/;
53.4;
SENTINEL
SENTINEL
```